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Internal Design of a Hydroponics Greenhouse for Tri Cycle Farms

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TABLE OF CONTENTS

LIST OF TABLES

LIST OF FIGURES

LIST OF EQUATIONS

PROJECT SUMMARY

Hydroponics is the agricultural technique of growing plants without soil, using other growing media and added nutrients in a solvent. It is an attractive agricultural method over conventional agriculture because it is more water efficient, is less labor intensive, yields higher quality crops in less time, and is easier to control. According to the Digital Journal, "hydroponics crop value is anticipated to grow to USD 27.29 Billion by 2022 at an estimated CAGR of 6.39% from 2015 to 2020" (Sawant, 2016). Alongside this growing market acceptance for hydroponics, there is also a local demand that requires only a small transportation cost. For the past several years, Tri Cycle Farms - a 501-(c)(3) non-profit urban farm in Fayetteville - has dreamt of building a hydroponics greenhouse because it would provide a source of sustainable financial income, a location for educational programming, and a means of battling food insecurity. Since August 2017, I have been working with Tri Cycle Farms to help make the hydroponics greenhouse project a reality. The objectives of this section of the overall project are 1) to determine desirable crops to be produced, 2) design the internal layout of the chosen greenhouse, and 3) design one hydroponics system using engineering design and fluid mechanics. This thesis report outlines the process of fulfilling these objectives, the justification behind the design decisions, and a discussion of the potential implications moving forward.

INTRODUCTION

Almost 870 million people across the globe do not have access to enough food, partially due to increasing population, unfavorable weather conditions like drought, low land productivity, and poverty (Food and Agriculture Organization of the United Nations, 2012). Conventional agriculture has been struggling to push past these obstacles to efficiently feed the world. As populations grow, agricultural land is overcome by residential needs. Unpredictable, poor weather conditions leave conventional farmers exposed and financially vulnerable. Low land productivity leads farmers to overwork the soil to meet quotas, leading to even more soil degradation, erosion, and fertilizer usage. Widespread poverty inhibits people from purchasing fresh produce, driving food insecurity and malnourishment higher and higher.

However, new agricultural techniques are being developed to fill these gaps, meet the needs of future generations, and advance production in ways humanity has never done before. One such agricultural technique is hydroponics, which grows plants without soil in a water-based, nutrient rich solution that can be altered to best suit each crop. Compared with conventional, soil-based agriculture, hydroponics is a more sustainable option both environmentally and economically. It requires less land and grows plants more densely, increasing the productivity of land acre-by-acre. It is protected from unfavorable weather conditions because it is generally stationed in controlled environment greenhouses, and has the added capability of year-round production (Spray & Spray, 2019). It is not reliant upon soil characteristics and does not contribute to increasing soil degradation, runoff, erosion, or fertilizer contamination (Christie, 2014). It is also up to 90% more water efficient because it recycles water in a closed-loop system, eliminating escape through soil infiltration or evapotranspiration (Christie, 2014). Lastly, it does not require the use of pesticides, because the risk of soil-borne diseases in plants is eliminated (Viviano, 2017). It is for these reasons that hydroponics is a promising agricultural technology to meet production needs of the future without sacrificing environmental sustainability.

Tri Cycle Farms is a 501-(c)(3) nonprofit urban farm located in Fayetteville, Arkansas whose mission is to battle food insecurity in Northwest Arkansas. Their mission stems from the shocking statistics that globally, one in nine people are undernourished (United Nations, n.d.), and in Northwest Arkansas, one in four children are food insecure (Feeding America, n.d.). For over five years, they have dreamt of owning a hydroponics greenhouse on-site because, through such a greenhouse, they hope to be able to generate a sustainable, self-sufficient profit on a premium product to keep their doors open, create a space for environmental education, and increase their impact on the battle against food insecurity in Northwest Arkansas. Tri Cycle Farms recognizes that hydroponics is an environmentally and socially sustainable agricultural method and would like to showcase these features through educational programming with a Hydro House "Seed to Sell" project on the farm. Since August 2017, I have been working in coordination with another student to help Tri Cycle Farms design this hydroponics greenhouse to address their specific needs while maintaining sustainability.

The objective of this project was to design the hydroponic system for the most profitable crop, a key requirement set by the client. The objectives were to 1) determine the crops to produce in the greenhouse, 2) design the internal layout of the greenhouse based on the plants chosen, and 3) size one system for the plants and layout specified. The first objective was accomplished in collaboration with a team of students in the SUST 4000 capstone course at the University of Arkansas who developed a survey for local businesses for a market analysis. This analysis was the basis of determining the plants to produce. The system's internal structure was then designed based on the plants chosen, taking into consideration commonly used hydroponic systems and the physical boundaries from the greenhouse structure within the requirements of Tri Cycle Farms. Finally, the system specifics were designed for one hydroponic system, including the sizing of pipes and pumps to accommodate the appropriate flow rates.

LITERATURE REVIEW

Types of Hydroponic Systems

Hydroponics is a growing agricultural method with several system variations, enabling farmers to grow a broad range of crops. A few types of hydroponic systems include wick systems, deep flow technique, nutrient film technique, ebb-and-flow, and shallow-aggregate ebb-and-flood. To design a successful hydroponics greenhouse, the specific hydroponic system chosen is a critical determinant.

Wick systems are arguably the simplest system and employ capillary action to pull water from a reservoir up to the aggregate which holds the roots of a plant (Sanders, 2016).This system is very simple to build but requires constant maintenance to ensure that the wicks are clean and capable of providing enough water to the plant's roots. It is not recommended for larger plants like tomatoes or for delicate plants like strawberries.

Deep flow technique (DFT) suspends plant roots in a 2-3 inch bed of nutrient solution which is able to flow around the roots (Maximum Yield, 2017). This works well for plants without deep roots and with short grow cycles, commonly herbs or lettuces and other leafy greens, but does not support larger plants or those with longer grow cycles. This system requires aeration to ensure that the water contains appropriate levels of dissolved oxygen for the plants.

Nutrient film technique (NFT) is among the most popular systems for commercial growing. It consists of channels that the roots are suspended in that allows nutrient solution to flow through constantly. This system is recirculating and provides a shallow flow that is referred to as a "film" of nutrients for the roots. This system is commonly used for leafy greens, herbs, and even strawberries. Plants with quick-growing roots are not recommended as they can cause too much resistance for the solution flowing through the channels (Espiritu, 2018).

Ebb-and-flow systems, commonly referred to as flood-and-drain, is a hydroponic method that operates on cycles of watering spread throughout the day. The roots are planted in a growing medium like clay pebbles and are flooded with the nutrient solution periodically, depending on the plant. Timers are used in this system so that it can be autonomous, and the water drains back into the reservoir once it floods the plants. This system is more efficient in terms of water and energy and is highly customizable, but does use more growing medium than most systems (No Soil Solutions, 2018). Drip systems are similar to ebb-and-flow except that the water is provided from above the plant and allowed to drain from a siphon. Both systems are commonly used in larger plants due to the stability of planting in a growing medium with cycled watering.

Shallow-aggregate ebb-and-flood (SAEF) is a hydroponic system developed by Joseph (JC) Chidiac that combines elements from NFT, ebb-and-flow, and DFT systems (Chidiac, 2017). The irrigation trays contain a shallow layer of aggregate that are flooded only 2-3 mm so that it uses the least energy and the least water of any of the previously introduced systems. This system works especially well for lettuce and other leafy greens.

Benefits of Hydroponics Agriculture

Due to design considerations, greenhouse environments can be controlled closely in terms of heat, humidity, sunlight, and ventilation (Rimol Greenhouse Systems, 2018). This level of control allows for the creation of ideal environments for crops, and can even help to improve the output. It also makes it possible for crops to be grown in their opposite season, a restriction that conventional agriculture faces. This term is dubbed “reverse seasonality” and is unique to plants that are grown in greenhouses. By creating synthetic environments for crops that mimic their ideal growing conditions, the hydroponic growers can enter the market without competing against conventional growers. Hydroponics does face uncertainties in its reliance upon equipment and user reliability, but the many benefits outweigh the risks.

METHODS OF DESIGN

Identifying Order of Operations

Before delving into the design calculations, I organized a series of actions that would serve as the order of operations. This was based on the project scope of both designing the internal layout of the greenhouse and designing the hydroponics systems. The order of operations is outlined below:

1. Choose a greenhouse, helping to ensure that it contains the necessary features.
    - Necessary features include appropriate doors and aisle space, the option for a head house addition, and a customizable structure per the client's request.
2. Identify the most important features for the client to reference while choosing a greenhouse and designing the internal layout.
    - Such features include educational programming considerations, leaving room for a growing station, including a variety of hydroponic systems to showcase, and including both built and bought hydroponic systems.
3. Design the internal layout of the chosen greenhouse, attempting to meet the client's needs.
    - This layout will need to include at least three different hydroponic systems, provide a comfortable amount of walking space for tours, contain doors located conveniently for tours and tending to hydroponic systems, and leave the space for a growing station.
4. Choose profitable plants based to be grown and sold in the greenhouse.
    - The most important factors in choosing crops will be the willingness of the local market to purchase the plants, the crop's likelihood for success in hydroponics agriculture systems, and a convenient pairing with another crop to grow in reverse seasons.

5. Consider different materials to use when designing hydroponics systems.
   - Before designing the systems and calculating pipe and pump sizes, I needed to know characteristics of the materials (such as PVC). These characteristics include roughness coefficient, shape (such as open channel or closed), friction factors, and the supplier.
6. Choose the best combination of hydroponic systems that will work with the chosen crops.
   - The systems needed to fit into the greenhouse well enough to not block light from other systems while also not wasting internal space, work with paired sets of crops so that the client can employ reverse seasonality, and be designed for enough space for each crop to not crowd in the system.
7. Perform the appropriate calculations for the designed hydroponics systems.
   - Necessary calculations include sizing the pipes and pumps for each system, comparing different design options such as splitting reservoirs between sub-systems, and respecting design restraints such as low flow rate.
8. Iterate designs and calculations to ensure that a favorable design is chosen.
   - Such iterations will include different quantities of hydroponics systems used, striving for maximum space efficiency while still meeting the seasonal market needs.
9. Finally, recommend designs to the client.
   - Final recommendations will include successful crops, appropriate systems, and the internal layout of the greenhouse specifically for selected crops in selected systems.

The order of operations is shown condensed in Figure 1 with considerations listed briefly below each operation step. Because there was only one system that was fully considered in this report, this order of operations can be used for future system design as well. Although all of the steps listed were followed during the actual execution of this project, organization was condensed for clarity in the remainder of this report.

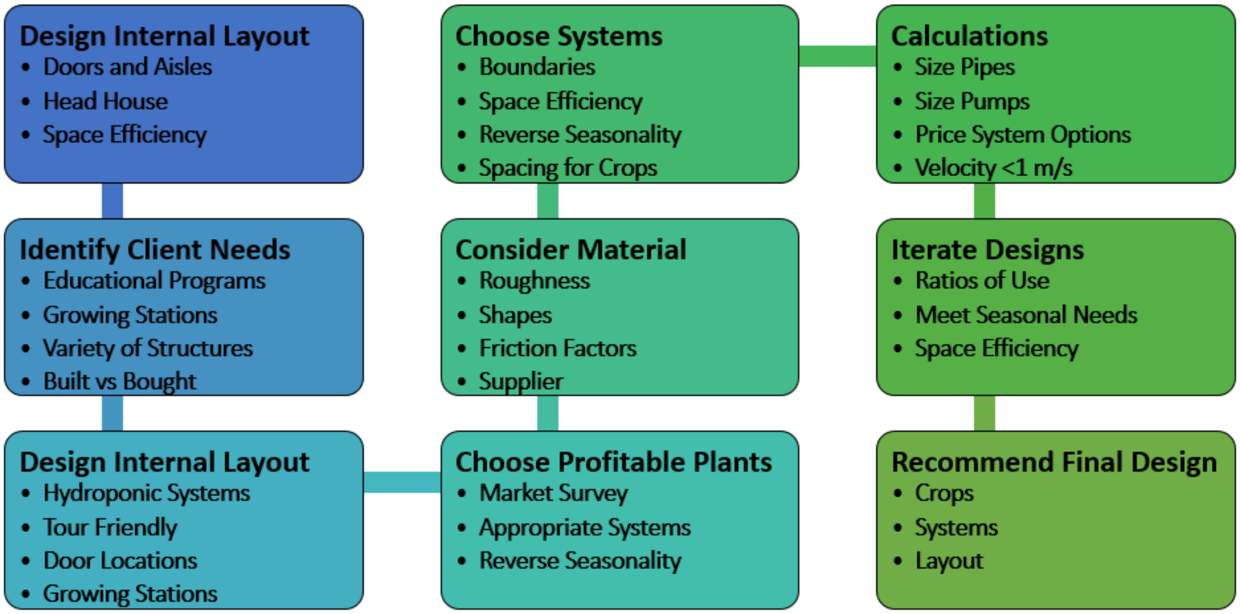

Figure 1. Condensed order of operations for project scope.

Objective 1: Determining Crops to Produce

The first phase of project design was to determine which crops would be most beneficial to produce, since the yields from the greenhouse will serve as the primary source of reliable income for Tri Cycle Farms. To do this, I worked closely with a team of students in the Sustainability Capstone course to develop a survey for local restaurants, co-ops, and grocery stores. Factors that are important for the client include an active market with buyers that will commit to regularly purchasing the hydroponic produce at a premium price, along with a market whose purchases will not be displacing other local farmers. For the purpose of determining profitable crops, I ensured that the team addressed the following questions:

1. Would your store consider carrying hydroponic produce?
2. Would you market hydroponic crops to your customers?
3. If so, at what price would you sell these products?

4. Are there any other hydroponics crops or herbs that you would be interested in marketing toward your customers?
5. What produce does your company lack during each season?
6. Would you be interested in collaborating with a local non-profit such as Tri Cycle Farms?

The combination of positive answers from the survey exposed what the willing, local market will desire in each season. The initiative will utilize the method of reverse seasonality, in which the typical growing seasons for crops is reversed - spring and summer crops grown in the fall and winter months. This method is attainable in a greenhouse setting due to higher environmental control capabilities and is ideal for Tri Cycle Farms to implement based on the desires of the local market while also eliminating the risk of competing with local conventional-agriculture farmers.

Objective 2: Designing the Production System Layout

Hydroponic Systems Selection

There are several traditional hydroponic systems that are used commonly among commercial and industrial farmers including ebb-and-flow, nutrient flow technique (NFT), deep flow technique (DFT), wick systems, and drip systems, among others. The client already possessed two complete hydroponic systems that had been donated previously: one 12-ft x 12-ft NFT system and one 4-ft x 8-ft DFT system. Once the crops were selected, I chose a hydroponics systems for each based on those commonly used and most likely to succeed for the specific crops, considering additional internal space-efficiency metrics.

Greenhouse Requirements

A reliable, high-quality greenhouse was needed to ensure that the client can produce the most yield and therefore the most profit. Tri Cycle Farms requested a state-of-the-art greenhouse with a maximum budget of $35,000. Because many greenhouses come with features such as windows, doors of various sizes, differing shell materials, and a wide range of sizes, the chosen greenhouse must have only the most pertinent features to ensure that the client will be receiving maximum value for money, especially considering it is a non-profit. We determined that space would be the most valuable asset because more space means more growth potential, which in turn means more profit potential for the client. Shell material was the second determining factor to be sure that the greenhouse will be appropriate for our region and to minimize heating and cooling costs. Windows will not be necessary in the greenhouse as they will not offer any functional benefit and will offer additional variables like light and heat to certain systems that would need to be considered in design calculations. The greenhouse will use as few doors as possible while maintaining ease-of-use for the operator and comfortable navigation for operators and visitors. Doors will be needed for access into the head house and the greenhouse from the outside, as well as a door from the head house into the greenhouse so that plants do not have to be exposed to the elements during transplantation.

Internal Design Considerations

The client gave several design constraints focused around the educational programming potential of the greenhouse in terms of environmental education for the community as well as research potential for university students. The first main objective for the completed hydroponics greenhouse will be to serve as a location for environmental education for community members of all ages and backgrounds. The client wishes to hold workshops and tours through the greenhouse so it is important that there is enough open space for up to 15 people to move through at one time. Due to this factor, it was determined that the walkways should be ~4-ft wide so that 2 people could walk through side-by-side if needed. During a workshop or tour, the instructor can stand between two systems as a focal point, facing the entire group, and the group can stand in 2 arcs composed of up to 8 people. The layout was designed so that the participants can directly see and pass by every system. Another design request was to implement a variety of structures so that visitors can experience a wide range of the potential that hydroponics has to offer. In the final design, the goal was to utilize three or more hydroponic systems to meet this constraint. Along with system type-variety, the design included generic systems that have been purchased as a whole, as well as customized systems that have been designed specifically for this greenhouse with cost in mind. It was important to the client that visitors can see systems that they could easily purchase themselves as well as systems that they could create themselves if they wish. The final design constraint was to consider the research potential for future university students. I determined that at least two replicates are needed to ensure that students could perform research such as comparing two factors, one as a control and one that has been manipulated in some way (for example, providing the crops with more nitrogen). To ensure unbiased foundation, the comparison systems would need to be identical in every other way. Therefore, the layout of the greenhouse contains identical systems, two or more of every kind from the structural components to the orientation within the greenhouse. Finally, the client would like a space for seed-starting, control system visibility and functionality, and potting. These needs were met with the addition of a head house which will be the location of the cold room and irrigation room.

Objective 3: Designing Hydroponic Systems

System Design Considerations

I chose to custom-design a hydroponic system that is utilized in the greenhouse due to the economical and functional advantages. I used the design form of Bernoulli's equation to determine how much work the pumps need to provide. The design form of Bernoulli's equation is shown in Equation [1].

$$W_{1-2} = (h_2 - h_1) + \frac{P_2 - P_1}{\gamma} + \frac{v_2^2 - v_1^2}{2g} + F_{1-2} \qquad [1]$$

I used the worst-reasonable-case to ensure that the chosen pump will be able to perform. All "Point 1's" are taken at the bottom of a reservoir and all "Point 2's" are at the outlet of a pipe or tube. The worst-reasonable-case assumptions made include the following, when applicable:

- The reservoir is empty, therefore pressure at point 1 is atmospheric
- Work calculations will use maximum reasonable velocity and flow rates
- Velocity at the inlet to the pump (Point 1) will be negligible
- Pump efficiency will be 10%

All of these assumptions will help to ensure that the calculated pump size will account for the head, pressure, momentum, and friction losses in the systems. Friction losses across the system were calculated using Darcy's formula, Equation [2], and the Colebrook equation, Equation [3]. Friction losses will be accounted for through every length of straight pipe, bend, sudden contraction, and nozzle.

$$F_{SP} = f\frac{L}{D}\frac{v^2}{2g} \qquad [2]$$

$$f = \frac{1}{4[\log_{10}\left(\frac{\varepsilon}{3.7D} + \frac{2.51}{Re\sqrt{f}}\right)]^2} \qquad [3]$$

Hydroponically grown crops have unique water requirements which were the first consideration for sizing pumps. Once water requirements are defined, the watering cycle frequencies and durations were be determined. These decisions were based off the following guidelines:

- Shorter frequencies are more desirable in drip systems (1-5 minutes)
- Velocity <u>must not</u> be greater than 2 m/s, ideally less than 1 m/s due to noise
- Each cycle must provide irrigation of at least 20% of the total volume of the container
- Friction loss from the point of release to the first plant must not exceed 1% of the total losses

These parameters were the basis of decision-making in determining the duration and frequency of each watering cycle and therefore the final flow-rate, momentum, and friction loss factors used to appropriately size the pump.

Separate reservoirs were necessary for each system, sized based upon a single day's water needs. I used a safety factor of 2.0 to be certain that the reservoir will be able to handle each system's needs and essentially double the daily water requirement per system. This excess will allow for expansion and account for any uncertainties.

I generated a bill of materials for each system iteration to present to the client with recommended equipment and general details about each, along with cost estimates. Each independent system required a reliable controller for the watering cycles, as these will occur only during the day when an operator can be nearby.

DESIGN RESULTS

Produce Decisions

Based on the positive results from the market survey, a desire to not displace current conventional farmers, the likelihood of success of a crop in hydroponic agriculture, and the businesses' willingness to pay premium prices for crops, I chose to grow crops rotationally in the greenhouse employing reverse seasonality. In the spring and summer seasons, the greenhouse can sell tomatoes, herbs, and leafy greens. In the winter and fall seasons, it can sell strawberries, herbs, tomatoes, and leafy greens. The herb with the highest volume of growth will be basil until Tri Cycle Farms employees become comfortable with the systems. Leafy greens like lettuce and spinach can succeed in many types of hydroponic systems and can be grown to replace other crops like herbs if they do not thrive in the market. The crops chosen were all desired in the market by consumers who are willing to pay a premium price for responsibly grown produce, are in need of the specific produce during seasons which local growers cannot currently provide, and are interested in purchasing from Tri Cycle Farms when the hydroponic produce becomes available.

Hydroponic Systems Chosen

Next, I chose hydroponic growing systems based on the chosen crops. Tomatoes grow best with cycled watering versus continuous watering, therefore the Dutch bucket is the most successful hydroponic technique for tomato. Dutch buckets are a low-footprint type of drip system in which the plants are grown from a bucket-like structure that can be arranged in series and watered during set frequencies and durations - this is also the most common system for tomatoes and is the system that was chosen. Herbs grow best in NFT systems, so the 12-ft x 12-ft system that Tri Cycle Farms already possesses will suffice. Strawberries have best yields in vertical systems, commonly referred to as strawberry walls, due to the efficiency of space. This system will be custom-designed based on previously successful, low-impact designs. Lettuce varieties grow very well in SAEF systems, so this system was chosen as the primary grower for lettuces. Generically, leafy greens grow well in NFT, SAEF, and DFT systems and can be cycled in-and-out of any of these systems if needed. DFT is suitable for herbs as well as leafy greens, and will be utilized since Tri Cycle Farms already owns one complete system. The employment of multiple systems that are suitable for more than one crop is a valuable characteristic of the overall design to allow room for Tri Cycle Farms to grow new crops if they would like. For each custom-designed system, the material chosen was PVC because it is food-safe, affordable, and easy to work with.

Final Greenhouse

The chosen greenhouse was a High Yield™ Insulated Greenhouse from Ceres Greenhouse Solutions headquartered in Boulder, Colorado. The retail price for the greenhouse is $37,300; however, after an in-person meeting with the Chief Operations Officer and design consultants, the greenhouse will cost Tri Cycle Farms only $22,000. The greenhouse is all-inclusive with windows, two doors, and ventilation and well below the designated budget of $35,000. This greenhouse includes 26 gauge, R-14 insulated metal walls, one single-door, and one double-door. The dimensions are 23-ft x 40-ft, the largest size that will fit in the allocated space at the farm, and allows for 920-ft^2 of production space. One of the 40-ft walls, along with the roof, is constructed entirely of 8-mm double-wall polycarbonate, with double air chambers that provide insulation. This is the side that will be south-facing on the farm. Because sunlight is not going to shine on all sides, the opposite 40-ft wall and both 23-ft walls are constructed of a non-transparent insulating material which is cheaper than commonly-used greenhouse Plexiglas and will help regulate temperature within the greenhouse. The roof of the greenhouse is angled to provide optimum light. A visual is shown in Figure 2, which was taken from Tri Cycle Farms' web page describing the project. Due to financial restrictions, the head house will implemented at a later date and may not be supplied from Ceres Greenhouse Solutions.

Figure 2. General greenhouse structure from Tri Cycle Farms (Tri Cycle Farms, 2018).

Internal Layout

Early iterations of the internal layout, shown in Figures 3 and 4, are displayed to provide reference for the transition from the first design through the final. Units shown in Figure 3 are in feet. Considerations that continuously influenced design iterations include maximizing space efficiency, utilizing more system variety, and understanding realistically how much space each system needed to take. Each iteration was critiqued by project advisor JC until a collaborative, mutual design was produced.

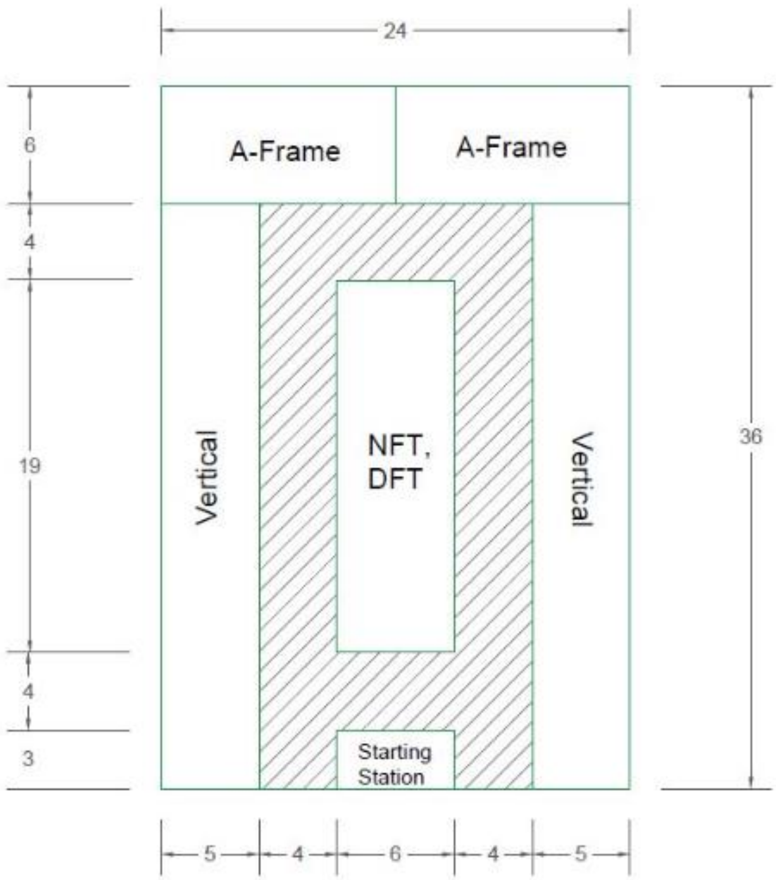

Figure 3. First iteration of internal layout.

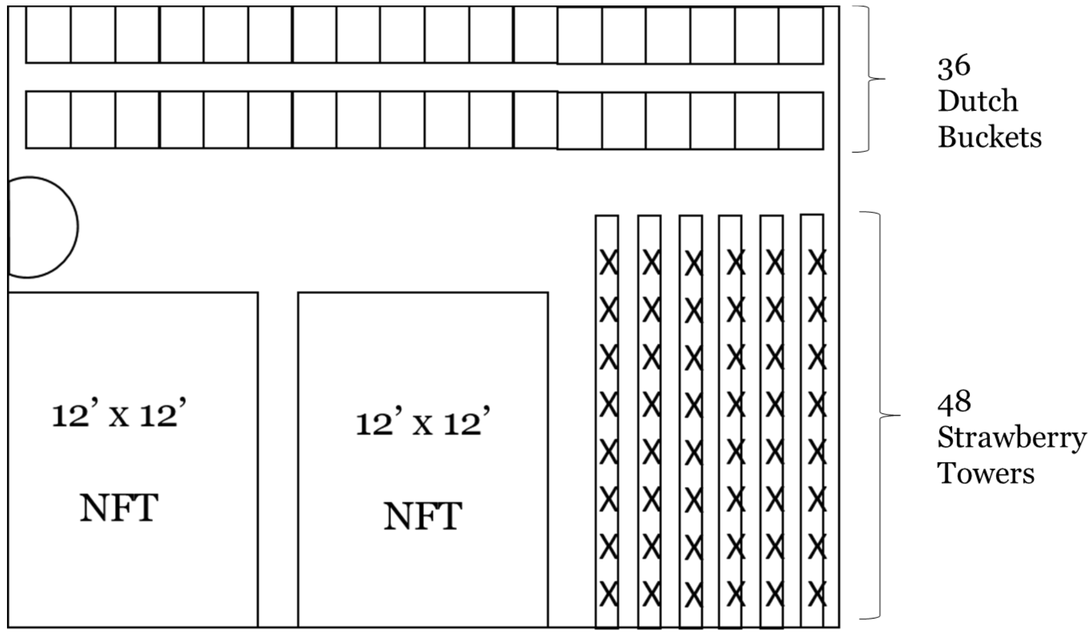

Figure 4. Early iteration for internal layout.

The final recommended design for the internal layout for the greenhouse is shown in Figure 5. The head house, an enclosed building attachment, will be a later addition and will contain two 10-ft x 8-ft spaces for a cold room and an irrigation room which will be used for starting seeds before transplantation into the hydroponics systems. It will also be used as general space for potting and seed-starting, tour introductions, and other applications. The irrigation room will contain a sink area where anyone entering the greenhouse can wash their hands to preserve sanitary integrity and protect the crops. Double doors will lead from the outside into the head house, with another set of double doors leading into the greenhouse space. The greenhouse will be accessible from these double doors as well as one pedestrian door for outside entry and exit. Dutch buckets are shown in alternating rows as dotted squares.

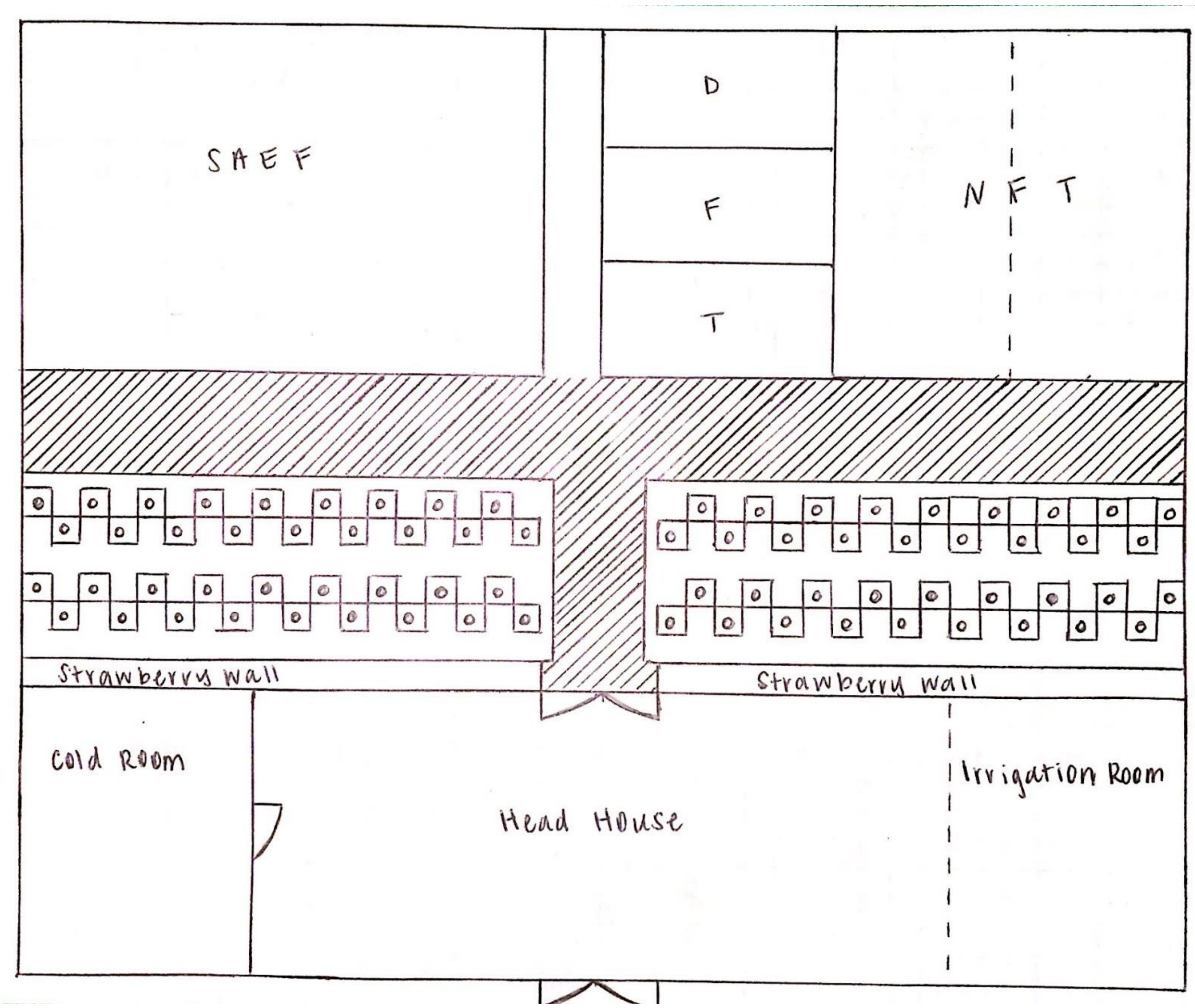

Figure 5. Final design recommendation for the internal layout.

Because tomato plants have the potential to grow up to 6-ft tall, the Dutch bucket systems were placed at the end of the greenhouse with the higher ceiling, near the head house. Dutch buckets take up about 1 square foot each and can be arranged in series to a customizable length. Through consultation with the client and project advisors, I have chosen to implement 72 Dutch buckets using four independent systems with 18 buckets each so that one, two, or three systems can be manipulated and compared to a control system. Strawberry walls will be built behind the Dutch bucket systems, along the north-side wall shared with the head house. This allows for strawberries to receive an even amount of sunlight without compromising the light available to any other systems. They will be designed to stretch as far as is reasonable, from the east- and west-facing walls to the double doors into the head house. The width of the walkway leading from the double doors from the head house and between the Dutch bucket systems will be ~4-ft wide, chosen to be sufficient for two people to walk through side-by-side. This walkway will expand into the middle of the greenhouse from the east- to west-facing walls, the full length of the greenhouse, so that all systems are accessible by visitors and operators.

The south-facing wall will be lined with the 12-ft x 12-ft NFT system, next to three 4-ft x 8-ft DFT systems, and then one 18-ft x 12-ft SAEF system. It was important that these shorter systems be in the front of the greenhouse because they will not block light from reaching the taller systems like the Dutch buckets and the strawberry walls. The NFT system is equipped with two reservoirs so that it can essentially be split in half with respect to nutrient availability for research purposes and comparative analysis between "two" identical systems. Three DFT systems were chosen due to their versatility with crop growth potential, advantageous dimensions compared to NFT and SAEF systems, and because Tri Cycle Farms already possesses one complete system. These systems will sit on rolling benches so that they can be moved two feet east-to-west for ease of access to either the SAEF or NFT systems. The SAEF system can be custom-designed to be any length or width in increments of two feet. The remaining space of 18-ft widthwise and 12-ft lengthwise, leaving room for navigation between the DFT system and not disrupting the linearity of the walkway, allowed for a large SAEF system capable of producing large amounts of lettuces or other greens. All systems, with the exception of the SAEF system, met the design requirement of research potential for future students who wish to compare identical systems with a single difference (for example, nutrient composition). All walkways are appropriate for groups of ~15 people and lead either outside or into the head house.

Dutch Bucket System Design

The first analysis performed was for the Dutch bucket systems for tomatoes. I ran iterations for capital costs on three system versions: using a combination of pre-manufactured systems comprised of one 10-bucket and one 8-bucket system per row for a total of four rows; designing the system from parts only, sized and customized; and using 72 independent systems purchased from a local hydroponics equipment store. The comparison for the bill of materials for each iteration is shown in Table 1, showing that the custom-designed system is the most cost-effective by far. Note that each individual bucket can support two tomato plants each, so the entire system will have the capability of producing 144 tomato plants at any time.

Table 1. Comparison of bill of materials for three options.

	Type	Details	Supplier	Units	Unit Cost	Total cost
	Benches	12"W x 7"H x 144"L	FarmTek	12	$152.95	$1,835.40
	Substrate	Clay, 40-L	FarmTek	18	$28.95	$521.10
Option 1: Buy 4*10-bucket systems and 4*8-bucket systems	Bucket system	10 buckets, equip	FarmTek	4	$739.00	$2,956.00
	Bucket system	8 buckets, equip	Viagrow	4	$278.95	$1,115.80
	Controller	--------------	Better Grow Hydro	16	$300	$4,800.00
						$11,228.30
Option 2: Purchase all components separately	Buckets only	Single bucket	FarmTek	72	$6.39	$460.08
	Accessory	Siphon elbow	FarmTek	144	$0.39	$56.16
	Accessory	Lids	FarmTek	144	$0.39	$56.16
	Return Line	1/2" sch 40 10-ft	Home Depot	8	$2.31	$18.48
	Pump	2/3 HP	---------------	4	$180.00	$720.00
	Controller	--------------	Better Grow Hydro	4	$300.00	$1,200.00
	Reservoir	55 gal 14" H	The Tank-Depot	4	$149.99	$599.96
	30 Drip emitters	2 GPH	Home Depot	3	$6.88	$20.64
	Stake Guide	1/8" x 250	Zen Hydro	1	$62.50	$62.50
	Tubing coil	1/2" x 100'	Home Depot	3	$11.98	$35.94
	Micro-tubing	3/16" x 100'	Zen Hydro	2	$11.44	$22.88
						$5,609.30
Option 3: Purchase 72 independent bucket systems	Bucket system	Independent	Hog City Hydro	72	$45.99	$3,311.28
	Controller	--------------	Better Grow Hydro	72	$300	21,600
						$27,267.78

The details of this system were established using calculations from fluid dynamics, unit operations, and general engineering judgement. A generic, common design for Dutch buckets is shown in Figure 6 for reference. Pipes were sized to be as small as possible while maintaining a system velocity below 1 m/s, using engineering design from unit operations and fluid mechanics.

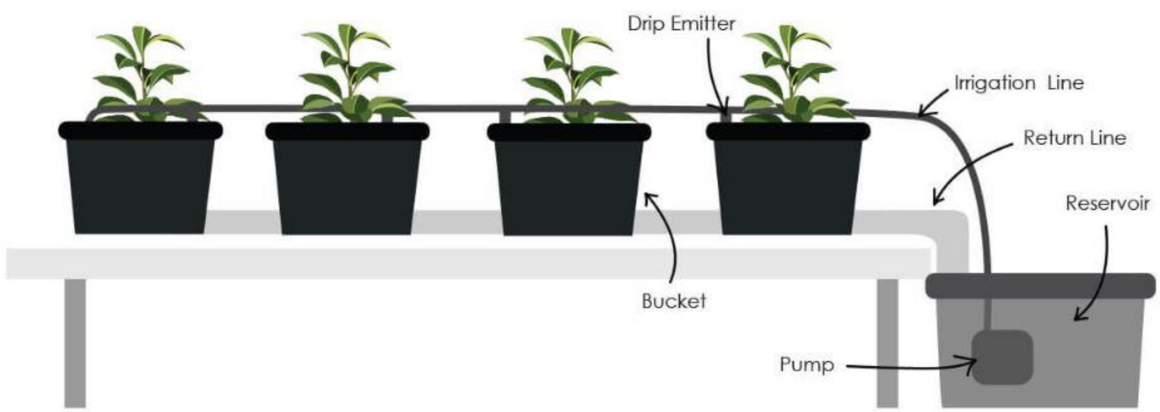

Figure 6. Generic Dutch bucket hydroponic system (Storey, 2016).

An example for sizing the return line using schedule 40 PVC pipe is shown in Table 2. The four designed sub-systems consist of 18 alternating buckets, benches to place the system on, a ½-in. main line, 2-GPH emitters for each individual plant connected to a 3/16-in. micro-tube then a ⅛-in. stake guide, clay aggregate as the grow-medium, a ½-in. return line, a reservoir, and a pump.

Table 2. Example calculation - sizing return line for Dutch buckets.

Material:	PVC			Flow Rate:	0.000189	m^3/s
Roughness:	0.0015	mm		ID:	0.015524	m
Temperature:	21	C		ID:	0.611171	in
Sizing Pipes						
Pipe Specs	Inside Diameter (in)	Area (ft^2)	Area (m^2)	Velocity (m/s)		
1/2" sch 40	0.622	0.0021101	0.0001960	0.965485		
3/16" sch 40	0.1875	0.0001917	0.0000178	10.624869		
Calculate Reynolds Number						
Fluid density (kg/m^3)	Dynamic Viscosity (Pa*s)	Velocity (m/s)	ID (m)	Reynolds		
998	0.000984	0.965485	0.015668	15341.95389		
If Re > 2130:	f'	0.061884		If f' >= 0.018	f	0.061884
If Re < 2130:	f'	0.004172		If f' < 0.018	f	0.055401
				Chosen f		0.061884
Colebrook Check						
f (1)	0.01335			Length Straight Pipe	5.4864	
f (2)	0.01183			Fsp (m)	0.1968	

For hydroponic tomatoes, the water requirement is 1-2 quarts per day per plant (A, 2015), equating to 36-72 quarts per day per system due to 18 buckets per system with two tomato plants each. With this water requirement, I was able to determine a range of potential flow rates depending upon the watering cycle durations. Tomatoes grow best under short watering cycles, ideally five minutes or less with shorter durations preferred (Lizarraga et al. 2003). I iterated designs in which the systems were watered at five-minute watering durations. The design constraints were low velocity (<1 m/s) due to noise, negligible friction loss (<1% of the total losses) from the first plant to the last in each sub-system, and providing at least 20% of total volume with water. I ran these iterations at five-, two-, and one-minute watering durations and determined the one-minute durations to be the most advantageous due to the lowest energy requirement for the pump. The selected duration and frequency will be six one-minute watering durations which will be spread evenly throughout the day while an employee is on-site; the tabulations are shown in Table 3.

Table 3. Friction loss calculations at 1-minute release intervals.

	Min Flow	Max Flow		Min Velocity	Max Velocity	Min Friction	Max Friction	Min Friction	Max Friction	Min Fsp	Max Fsp
Water in 1-min cycles	Q (m^3/s)	Q (m^3/s)				Loss	Loss	Loss	Loss	Difference	Difference
	0.034	0.068	m^3/day	V (m/s)	V (m/s)	Fsp (m)	Fsp (m)	Fsp (m)	Fsp (m)	Fsp (m)	Fsp (m)
						At Qmin		At Qmax			
if one 1-min release:	0.034	0.068	m^3								
	0.001	0.001	m^3/s	2.897	5.794	1.549	5.897	0.086	0.328	1.463	5.570
	9.000	18.000	gal								
	1.800	3.600	gpm								
if two 1-min release:	0.017	0.034	m^3								
	0.000	0.001	m^3/s	1.448	2.897	5.897	1.549	0.328	0.086	5.570	1.463
	4.500	9.000	gal								
	0.900	1.800	gpm								
if three 1-min release:	0.011	0.023	m^3								
	0.000	0.000	m^3/s	0.966	1.931	0.197	0.717	0.011	0.040	0.186	0.678
	3.000	6.000	gal								
	0.600	1.200	gpm								
if four 1-min release:	0.009	0.017	m^3								
	0.000	0.000	m^3/s	0.724	1.448	0.116	0.418	0.006	0.023	0.110	0.395
	2.250	4.500	gal								
	0.450	0.900	gpm								
if five 1-min release:	0.007	0.014	m^3								
	0.000	0.000	m^3/s	0.579	1.159	0.077	0.276	0.004	0.015	0.073	0.260
	1.800	3.600	gal								
	0.360	0.720	gpm								
if six 1-min release:	0.006	0.011	m^3								
	0.000	0.000	m^3/s	0.483	0.966	0.055	0.197	0.003	0.011	0.052	0.186
	1.500	3.000	gal								
	0.300	0.600	gpm								

Using Bernoulli's equation, I derived an equation to calculate the work required by a pump for each Dutch bucket system which will account for losses due to head, momentum, pressure, and friction at the worst-reasonable-case scenario. At an assumed pump efficiency of 10%, each system required a ⅔ HP pump. Table 4 shows the calculation components used in the equation, based on the six one-minute watering durations.

Table 4. Using Bernoulli's equation to size Dutch bucket pumps.

h_1 (m)	h_2 (m)	P_1 (Pa)	P_2 (Pa)	v_1 (m/s)	v_2 (m/s)	$F_{sp\,(1/2")}$	$F_{sp\,(3/16")}$	F_{nozzle}	$F_{elbow(1)}$	F_{tee}	$F_{reducer}$	F_{bends}
0	0.914	0	0	0	0.966	0.197	0.147	0.003	0.047	0.879	0.046	0.048

W (m)	Po (W)	Po (HP)	Po (HP) 10% Eff	Pump Needed
25.558	47.361	0.063	0.635	2/3 hp

I then sized the reservoirs to be capable of holding one day's water requirement at a safety factor of 2.0, resulting in a minimum 36-gallon reservoir. I ran a second iteration of the design calculations assuming there would be one pump shared between two sub-systems to compare capital costs. The final tabulation is located in Table 5, showing that it would have been $500 cheaper to purchase one pump between two sub-systems rather than one pump per sub-system. After consultation with JC, I decided that one pump per sub-system was a safer option because if anything went wrong with a pump then it would negatively affect 36 plants rather than 18 with a shared pump which could cause over $500 just in profit losses. In this case, the risks outweigh the reward and one pump will be used per sub-system, requiring a total of four ⅔ HP pumps for the four Dutch bucket sub-systems. The reservoirs chosen in the cost estimation held 55 gallons each, which is well over the 36-gallon minimum requirement.

Table 5. Capital cost comparison for Dutch bucket system design alternatives.

One Pump per Sub-System	One Pump per Two Sub-Systems
$5,600	$5,100

DISCUSSION AND FUTURE OPPORTUNITIES

Moving forward, there is still much work to do before the full greenhouse design is complete. Although there is a fully sized and complete design for the Dutch bucket system for tomatoes, the other four systems to be used in the greenhouse still need to be designed and sized. These systems include the NFT, DFT, SAEF, and strawberry wall vertical systems. In addition, the energy and economic analyses of each system and the entire structure will need to be completed. The contract with CERES Greenhouse Solutions has been signed by Don Bennett, and excavation has been approved for the greenhouse on site at Tri Cycle Farms. Unfortunately, construction of the greenhouse and systems will begin after my graduation but the project will be left in good hands; a student team from biological engineering and other disciplines has been recruited and assembled to take over responsibilities for the initiative.

Once the hydroponics greenhouse is fully assembled, it will be the site of the Hydro House "Seed-to-Sell" Program for Tri Cycle Farms, a compliment to educational programming, farm tours, and service learning opportunities for University of Arkansas students. The internal layout of the greenhouse has been designed to ensure that there is enough walkway space between systems so that tour groups may comfortably fit inside and view the tour guide. In addition, each system was designed to be interactive for such tours so that guides can easily reach systems to demonstrate how they function and have access to the plant. The greenhouse will also be a community structure in its aesthetic. The client envisions the north side of the wall, which is not made of transparent greenhouse glass material, to be painted by a local artist or arts student into a mural. The mural will represent the community effort that has brought the project to life while also showcasing a welcoming image to promote more community involvement.

In addition to the community involvement aspect of the greenhouse, Tri Cycle Farms also envisions opportunities for University of Arkansas students. A large portion of the regular volunteers are already college students, and the client has a goal of creating a space where students can conduct research outside of an explicitly academic setting. The internal layout of the greenhouse also meets this goal by ensuring that there are at least two separate entities per hydroponics system type, sans the SAEF system. In the case of the Dutch buckets there are four separate sub-systems, each with its own water reservoir. This duplicity enables students to consider how altering different features may affect the crops while also allowing for a control group. In addition to research potential, the client also imagines opportunities for students to have internships centered on tending to specific hydroponic systems for a semester.

The internal layout and design of a single hydroponics system is only the beginning of this larger community initiative. Once the greenhouse is ready for assembly, Tri Cycle Farms will be hitting the ground running. A team of volunteers and project managers has been recruited and will be ready to take ownership of the student leadership once I graduate, leaving the Farm in their capable hands. Immediate next steps are to coordinate an introduction to the farm owner Don Bennett and project advisor JC Chidiac, along with a hand-off of work to-date. The intention is that future students will be able to design the rest of the systems and spearhead educational programming. The greenhouse will also feature a head house, which will be attached to the main portion of the greenhouse that has already been purchased. The head house will include an irrigation room and a cold room, which will be used for starting seeds before transplantation into the hydroponics systems. Tri Cycle Farms will also need to hire a full-time employee to maintain the greenhouse and provide leadership for student volunteers and researchers.

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